Renewable and Sustainable Energy Reviews 20 (2013) 430–442

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Application of solid oxide fuel cell technology for power generation—A review

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A R T I C L E I N F O

Article history:
Received 16 April 2012
Received in revised form
7 November 2012
Accepted 8 November 2012
Available online 11 January 2013

Keywords:
SOFC
Cogeneration
Trigeneration

A B S T R A C T

Solid oxide fuel cells (SOFCs) have been considered as one of the most promising technologies for very high-efficiency electric energy generation from natural gas, both with simple fuel cell plants and with integrated gas turbine/steam turbine–fuel cell systems. The high temperature exhaust gas from SOFC can be utilized in other cycles i.e. Rankine, Brayton for additional power generation or for heating and cooling purpose (cogeneration/trigeneration). The analysis shows that the resulting maximum efficiency of this SOFC-combined system can be up to 90% depending upon the operating condition and configuration used. This paper reviews the application of SOFC technology in power generation sector. This paper also investigate the research work undertaken or going on in this field.

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1. Introduction

Fuel cell is an energy conversion unit that converts a gaseous fuel to electrical energy and heat by electrochemical combination of a fuel with an oxidant. Since it is operated electrochemically and is not limited by the Carnot cycle, lower emissions such as NO_x or CO_2 are produced from fuel cells compared to the cleanest combustion process. Due to its high conversion efficiency and environmental acceptability, the fuel cell is regarded as an effective process to produce electricity from chemical components. The application of fuel cell technologies to advanced power generation systems signifies the most significant advancement in energy conservation and environmental protection for the next decade [1].

One such technology is the solid oxide fuel cell (SOFC), which is one of the most efficient and environmental-friendly technologies available for generating power from hydrogen, natural gas, and other renewable fuels. Large-scale, utility-based SOFC power generation systems have reached pilot-scale demonstration stages in the US, Europe, and in Japan. Small-scale SOFC systems

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http://dx.doi.org/10.1016/j.rser.2012.11.031

Nomenclature

SOFC	Solid oxide fuel cell
PEMFC	Proton exchange membrane fuel cell
GT	Gas turbine
ST	Steam turbine
DOE	Department of energy
MGT	Micro gas turbine
TIT	Turbine inlet temperature
CPO	Catalytic partial oxidation
ASR	Adiabatic steam reformer
HRSG	Heat recovery steam generator
CHP	Combined heat and power
CCHP	Combined cooling heating and power
HVAC	Heating, ventilation and air conditioning
IGFC	Integrated gasification

are being developed for military, residential, industrial, and transportation applications [2]. SOFC is an energy conversion device that converts the chemical energy of the fuel gas directly into electricity and therefore very high electrical efficiency can be achieved. SOFC uses an oxide-ion conducting ceramic material as the electrolyte. It is therefore simple in construction than all the other fuel cell system as only two phase are required (gas and solid). The electrolyte management issue that arises with other fuel cell is absent here. Moreover because of their high temperature of operation (600–1000 °C), natural gas fuel can be easily reformed within the cell, promotes rapid electro catalysis with nonprecious metals and produce high quality by product heat for cogeneration/trigeneration etc. Also pressurized SOFC can be successfully used as replacement for combustors in gas turbine or steam turbine. Such combined SOFC–GT or ST power system is expected to have efficiency over 70%. One of the main advantages of SOFC over other fuel cell is their ability to handle a wide range of hydrocarbon fuel. Quite vibration free operation of SOFC also eliminates noise usually associated with conventional power generation system.

There are several other review papers in literature involving the future aspects of power generation and challenges in the commercialization of SOFC system. A comprehensive study was carried out by Singhal [3] who investigates the advances in SOFC technology in power generation sector. Stambouli and Traversa [4] investigate the prospect of SOFC technology as an environmentally clean and efficient source of energy. Wachsman and Singhal [5] examined the commercialization, research and challenges of SOFC. Most of these review papers emphasize more on the research challenges for commercialization and development of SOFC technology. Very few papers have emphasized on the research issues of SOFC technology for residential, marine, industrial, and transportation applications.

This review paper discusses some application of SOFC in the power generation sector and summarizes the relative prospects and the competitive force of SOFCs in these fields. This paper also outlines some of the research challenges regarding the commercialization of SOFC.

2. Research challenges for the commercialization of SOFC

The technical root of fuel cell begins in 1930s when two Swiss Scientists experiments with Zinchronium and other elements as electrolyte. In 1950s GE and other company started experiments using SOFC but failed because of melting of cell material, short circuited etc. Currently researches are going on to reduce the cost of SOFC and develop it for small application like residential and transportation (100 kW). The DOE's SECA programme is attempting to develop SOFC modules that cost no more than 700 $ per kW [6] and large systems that are greater than 100 MW. In 1999 DOE has taken initiative to promote the development of environment friendly SOFC. Recent publicity may have created the impression that Bloom Energy's "Bloom Box" which is SOFC based power generating system (100 kW powered by natural gas) is available for residential power generation and that it will be used for distributed power generation also. The Bloom Box ES 5000 energy server offered currently is at a quoted price of 800,000 dollars and is 100 kW units [7]. The challenges for the commercialization of the fuel cell are to reduce cost and increase the reliability of the system. These challenges extend from the cell itself, to the stack interconnect and seals, to the balance of plant. Tremendous research are going in the field of lowering the operating temperature of SOFC from 1000 °C to less than equal to 800 °C and to reduce the startup time, for cost, reliability and portable power application and transportation [8].

3. Review of SOFC application and its prospect

Basically, SOFC have been investigated as an innovative technology that can be integrated with traditional electrical power plants or to supply electricity as on-site power generators [9]. Due to the fast development of industrial and social structure, the diverse application of SOFC in different field has been investigated. There are three main application of SOFC such as combined cycle power plant, cogeneration/trigeneration and residential application. Due to its high operating temperature, SOFC are not suitable for portable application and transportation. But now researchers are investigating in the areas to reduce the operating temperature of SOFC to make it suitable for portable application.

There are six different types of fuel cells available in the market. Out of these only PEMFC (80 °C) and SOFC (1000 °C) have captured the most part of the market share. As these two types of fuel cells are targeted for commercialization in the residential (1–10 kW), power generation (several MW) and commercial (25–250 MW) end use markets, system studies in this area are of great interest. The basic components of a SOFC power plant consist of a fuel processor, desulphurizer, fuel cell power module, power conditioning equipment for DC-AC converter and process gas heat exchanger. Depending upon the operating temperature SOFC fuel cell produce varying grades of waste heat that can be recovered for heating, cooling, cogeneration or trigeneration application purpose. It can significantly impact the system efficiency, economics and environmental issues. Hydrogen and carbon mono oxide are used as the fuel for SOFC. In order to supply these components to the fuel cell, steam reforming reaction is used to reform hydrocarbon fuels such as natural gas. Due to the high temperature of SOFC, reforming can be done very efficiently. Natural gas contains organic sulphur that can deactivate the steam reforming catalyst. So to ensure long life of the fuel processor unit, desulphurization is done before reforming shown in Fig. 1 [9]. Reforming can be internal or external. The external feed such as methane (natural gas) is converted to hydrogen and CO at the reformer section. In external reforming, the endothermic steam reforming reaction and the fuel cell reaction are operated separately in different units and there is no direct heat transfer between both unit operations. In case of internal

reforming, the endothermic reaction from the steam reforming reaction and the exothermic reaction from the oxidation reaction are operated together in single unit and therefore there is no need of separate reforming unit. There are two internal reforming concepts: direct and indirect internal reforming. Indirect internal reforming physically separates the reforming process from the electrochemical process, making use of the cell-stack heat release either by radiation heat transfer [9] or by direct physical contact between the cell hardware and the reforming unit. In direct internal reforming, the hydrocarbon fuel–steam mixture is admitted directly into the anode compartment and the fuel is reformed on the porous, nickel-based anode layer (Fig. 2).

3.1. Combined gas turbine power system with solid oxide fuel cell

This concept was first analyzed by Ide et al. [11] who compared the net plant efficiency of three types of fuel cell generation system. The efficiency losses of power generation processes are largely due to high irreversible fuel combustion. It can be improved by preventing the direct contact between air and fuel as it occurs in fuel cells. Theoretical studies of combined SOFC–GT cycles have attracted increasing attention worldwide by researchers. There are several other previous works in the literature involving thermodynamic analysis, design, modelling of SOFC–GT power system [8,10–28]. Massardo and Lubelli [8] developed a mathematical model that simulated the fuel cell steady-state operation of an integrated internal reforming SOFC–GT combined cycle. Costamagna et al. [12] investigate the design and analysis of a hybrid system, based on the coupling between a recuperative micro gas turbine (MGT) with a high-temperature SOFC reactor. Similar work has been performed by Chan et al. [13,14], Calise et al. [15], Yang et al. [16], Araki et al. [17], Park et al. [18] and Granovskii et al. [19].Granovskii et al. performed an exergy analysis to determine their efficiencies and capabilities of generating power at different rates of oxygen transport through the SOFC electrolyte. Cocco and Tola [20] investigate the performance analysis of SOFC–MGT power plants fuelled by methane and methanol. Haseli et al. [21] performed an exergy analysis of combined gas turbine power system with solid oxide fuel cell. The thermal efficiency of a conventional GT plant has significant losses due to the high irreversibility within the combustion chamber. A fuel cell–GT hybrid system represents an emerging technology for power generation because of its higher energy conversion efficiency, low environmental pollution and potential use of renewable energy sources as fuel. The thermal efficiency varies depending upon the cycle configuration and proposed layout of the hybrid system. Past work indicates an efficiency of up to 60% can be achieved with the integrated cycle (Table 1).

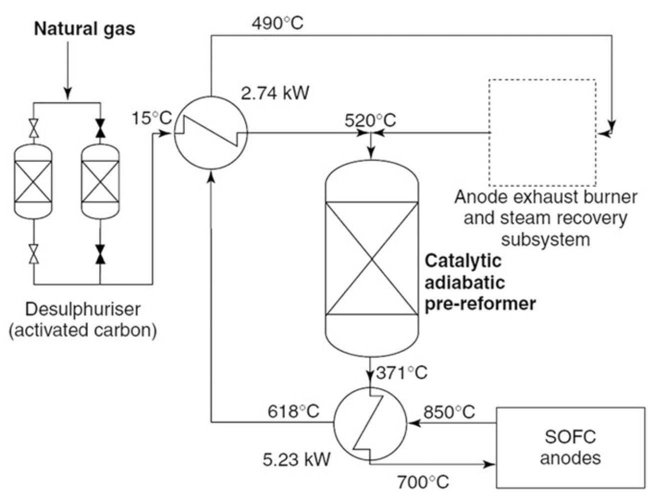

Fig. 1. Pre-reformer system devised for a Siemens 50-kW SOFC demonstration [9].

GT–SOFC system consist of six components: air compressor, recuperator, high temperature SOFC, combustor, gas turbine and power turbine. Generally, gas turbines can be connected to the SOFC in two different ways: indirect (Fig. 3) and direct (Fig. 4) integrations. In the former, the combustor of the gas turbine is replaced with a heat exchanger in which air from the compressor is heated by the fuel cell exhaust (Fig. 3). Under the indirect SOFC–GT hybrid system, the SOFC can be operated at atmospheric conditions. Although, it reduces the sealant requirement in the SOFC stack, the heat exchanger has to operate at very high temperatures and pressure differences. The material requirements in the indirect integration of SOFC–GT are really an issue and hence, it is not generally used. In the latter, the SOFC is directly integrated with the GT by replacing the combustion chamber of the GT as shown in Fig. 3. The pressurized air from the compressor is pre-heated by the exhaust gas from the power turbine before it enters the anode side of SOFC. Methane (natural gas) enters the cathode side of SOFC. The outlet air from cathode is used to burn the residual hydrogen, carbon dioxide and methane in the anode outlet gas. The products of chemical reaction are very lean; hence we supply additional methane injection into the combustion chamber in order to stabilize the

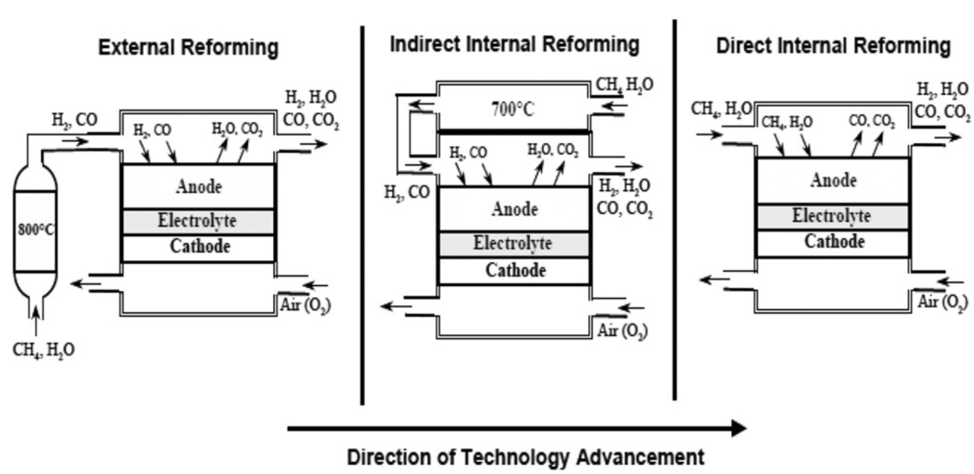

Fig. 2. Fuel cell configurations [10].

Table 1
Survey of thermal efficiencies of combined SOFC–GT plants in past literature.

Efficiency	System configuration	References
68.1	Pressurized cycle using an SOFC and integrated GT bottoming cycle	22
60	Gasification process linked with an SOFC and GT	24
60-65	Pressurized SOFC–GT combined cycle	30
70 <	Pressurized SOFC–GT cycle with a heat recovery bottoming cycle	25
60 <	Recuperated micro-gas turbine (MGT) with a high-temperature SOFC	12
60 <	SOFC stack, combustor, GT, two compressors and 3 recuperators	14
60	50kW micro-turbine coupled with a high-temperature SOFC	49
66.2	Pressurized tubular SOFC combined with an intercooled-rehear GT	29
69.1	Humid air turbine (HAT) cycle incorporated with the above cycle	29
76	Dual SOFC-HAT hybrid cycle	29
60 <	Internal-reforming (IR) SOFC–GT power generation system	13
70.6	Combined SOFC-GT system with liquefaction recovery of CO_2	31
65	30 kW GT–SOFC hybrid system	26
65.4	IR tubular SOFC-GT plant with 3 heat exchangers and mixers	15
60	1.5 MW integrated IRSOFC with two GTs and one HRSG	27
56.1	Two-staged low and high-temperature SOFC power generation cycle	14
68.5	Multi-staged SOFC/gas turbine/CO_2 recovery power plant	28
59.4	Recuperated GT integrated with SOFC	50
68.7	Recuperated GT with compressor air intercooling and two SOFCs	50

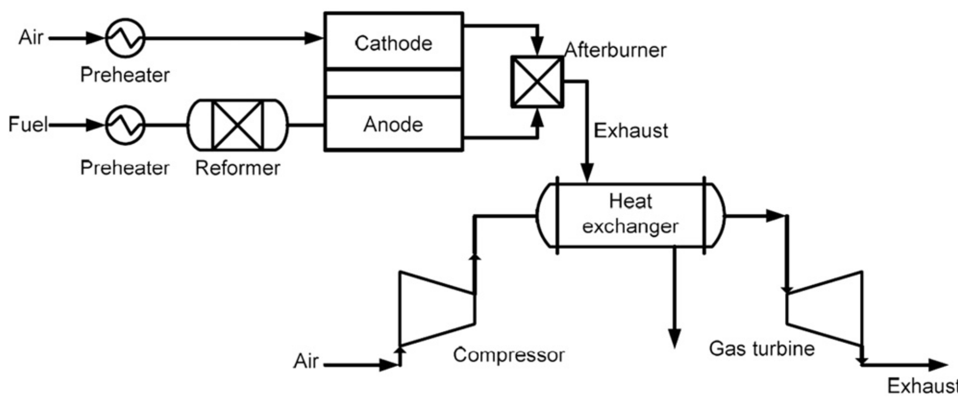

Fig. 3. Schematic of combined gas turbine power plant with SOFC (indirect) [10].

combustion. The extra fuel is supplied not For increasing the turbine inlet temperature. The fuel gas from combustion chamber is expanded in the turbine and preheats the compressor outlet air in the recuperator. When SOFC–GT model was analyzed under standard operating condition it was found that increasing the turbine inlet temperature (TIT), thermal efficiency of plant and exergy efficiency reduces but it improves the specific power output of the cycle. An increase in either TIT or compression ratio leads to higher rate of exergy destruction of the plant [8,10–29].

3.2. Integrated solid oxide fuel cell with Rankine cycle

A hybrid system consisting of SOFC on the top of a steam turbine is investigated by Rokni [32]. The plant is fired by natural gas. A desulfurization reactor and pre-reformer are fitted in the plant. The desulphurizer reactor removes the sulphur content in the fuel while the pre-reformer breaks down the heavier hydrocarbon. The pre-treated fuel then enters into the anode side of the SOFC. The remaining fuels after the SOFC stacks enter the burner for further burning. The exhaust gasses are then utilized to produce steam for a Rankine cycle in a heat recovery steam generator (HRSG) (Fig. 5). Different configurations of this system are suggested by Rokni. Cycle efficiency of up to 67% can be achieved by this system which is higher than any other conventional GT based power system. Some companies are investigating in this field e.g. Fontell et al. [33]. SOFC system is also combined with some combined cycle to achieve high electrical efficiency [34,35]. The investigations in the field of combined SOFC–steam turbine are very limited (see Dunbar et al. [36]).

Both catalytic partial oxidation (CPO) and adiabatic steam reformer (ASR) pre-reforming process can be used in SOFC–ST system. The efficiency of the system depends on the type of pre-reforming process used. It is found that efficiency of the system with ASR type is higher than CPO type. Decreasing the SOFC fuel utilization factor increases plant electrical efficiency but this parameter cannot be less than certain value otherwise TIT will increase which reduces the efficiency of the plant. So the efficiency of the SOFC–ST combine cycle can be increased by changing the configuration of the system.

3.3. Cogeneration with SOFC

In conventional power plant, efficiency is only 35% and remaining 65% of energy is lost. The major source of loss in the conversion process is the heat rejected to the surrounding water or air due to the inherent constraints of the different thermodynamic cycles employed in power generation. Also further losses of around 10–15% are associated with the transmission and distribution of electricity in the electrical grid. Cogeneration or Combined Heat and Power (CHP) are defined as the sequential generation of two different forms of useful energy from a single primary energy source, typically mechanical energy and thermal

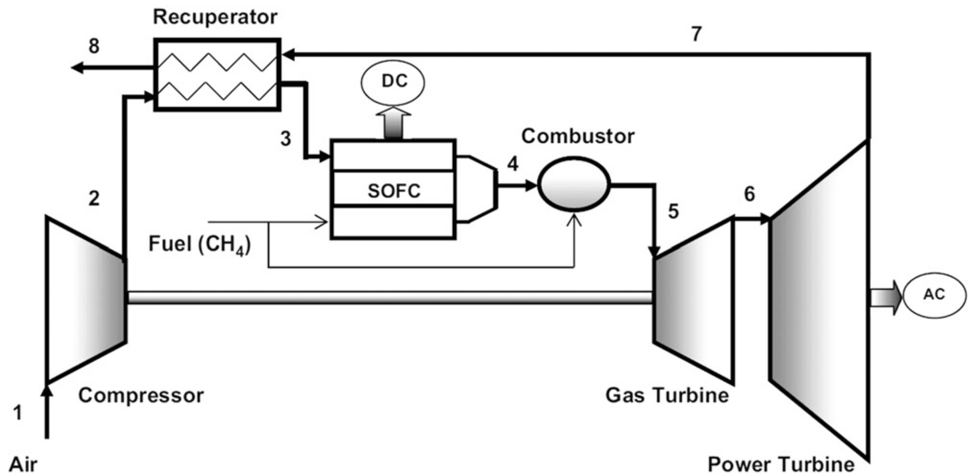

Fig. 4. Schematic of combined gas turbine power plant with SOFC (direct) [21].

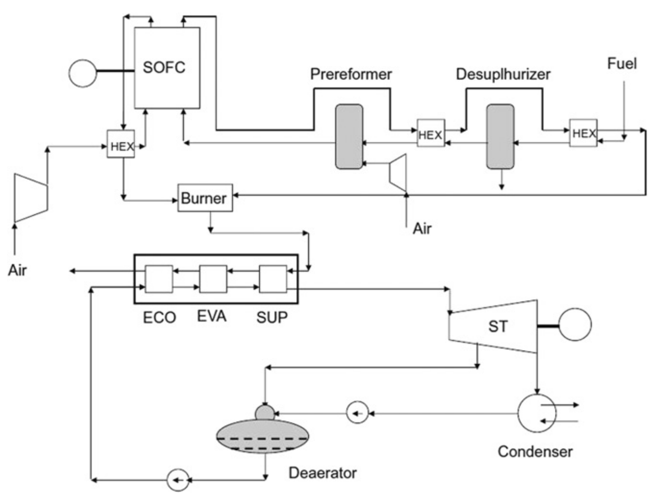

Fig. 5. Combined SOFC–Steam cycle plant [32].

energy. Mechanical energy may be used to drive an alternator for producing electricity, or rotating equipment such as motor, compressor, pump or fan for delivering various services. Thermal energy can be used either for direct process applications or for indirectly producing steam, hot water, hot air for dryer or chilled water for process cooling. The high temperature exhaust gas from SOFC can be utilized for heating purpose. It may be utilized in energy requiring units like preheaters and reformer, to preheat the air before it enters the combustion chamber or it may be used to generate steam in Rankine cycle. Thus the high-quality of waste heat and electrical energy can be cogenerated in SOFC systems. The integration of CHP with SOFC is a challenging task and researches are still going on in this field. It is found that the efficiency of the system can be increased greater than 80% by cogeneration. Chan et al. [37] investigate SOFC power system fed by hydrogen and methane. The hydrogen fed SOFC system consist of two preheaters, an SOFC stack, and an afterburner. The unreacted fuel from SOFC is burnt in an afterburner and the heat generated was supplied to the reformer, vaporizer and preheater. But the methane fed SOFC system is slightly complex. It consists of a mixer, a vaporizer, two preheaters, an external reformer, an SOFC stack, and an afterburner. Result of the analysis of the two system shows that the efficiency of the methane fed system is higher than those of hydrogen fed system. Fontell et al. [38] examined a 250 kW natural gas-fed SOFC plant. He incorporated a desulphurizer unit to remove the sulphur content in the fuel. The system shows that the exhaust gas from anode side of SOFC is used to preheat the reformed fuel. It then splits into two parts: one part is combusted in the afterburner with the air from the cathode side; the other part is recilculated and mixed with the inlet fuel stream before being fed to the pre-reformer. The exhaust gas from the afterburner is used to vaporize the water stream and preheating the natural gas feed stream. The efficiency of the system can be achieved up to 85% with cogenerating SOFC with CHP. Omosuna et al. [39] analyzed the integration of SOFC with biomass gasification for the production of power and heat simultaneously. He made a comparison between two different systems of 200 kW SOFC-CHP. One system uses hot gas cleanup process while the other uses cold gas cleanup process. The result of analysis showed that efficiency of the hot process is higher than that of the cold process because of better heat management in the cleaning process and higher gasification temperature. But the cost of the hot process is higher than that of the cold process. Bang-Møller et al. [40] performed an exergy analysis and optimization of a biomass gasification, solid oxide fuel cell and micro gas turbine hybrid system. The proposed system is divided into two parts: a gasification part and a CHP producing part. Wood chips are converted to product gas in the gasification part, and in the CHP producing part, the product gas is converted to electric power and heat by use of an SOFC stack and a MGT. The analysis of the system reveals that the greatest exergy destruction is caused by gasifier reactor. The optimized hybrid plant produced approximately 290 kW at an electrical efficiency of 58.2% based on lower heating value (LHV) (Fig. 6).

Zink et al. [41] examined an integrated solid oxide fuel cell (SOFC) absorption heating and cooling system used for buildings. The result of the analysis showed that such a system has the capacity to produce electric power, heating and/or cooling for buildings and the total system efficiencies of higher that 87% in different modes could be achieved. Another analysis in this area was done by Braun et al. [42]. He explored the application of SOFC-CHP system in residential dwelling through modelling and simulation of cell stack including balance of plant equipment. Five different SOFC system designs are evaluated in terms of their energetic performance and suitability for meeting residential thermal-to-electric ratios. The results indicate that maximum efficiency is achieved when cathode and anode gas recirculation is used along with internal reforming of methane. System electric efficiencies of 40% HHV (45% LHV) and combined heat and power efficiencies of 79% (88% LHV) are described. Colson et al. [43] presents a system model, developed using MATLAB/Simulink, for a 1.0-MW SOFC-CHP power plant and evaluates its ability to

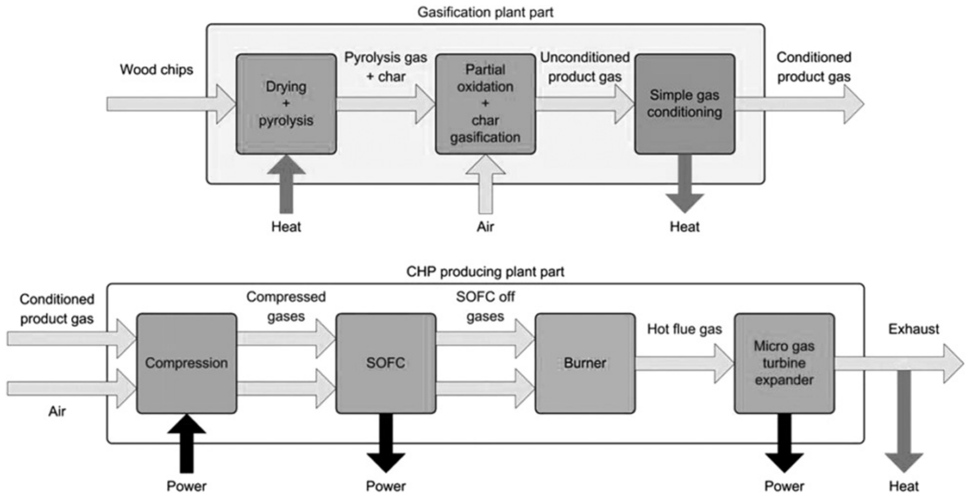

Fig. 6. SOFC–GT system with gasification plant [14].

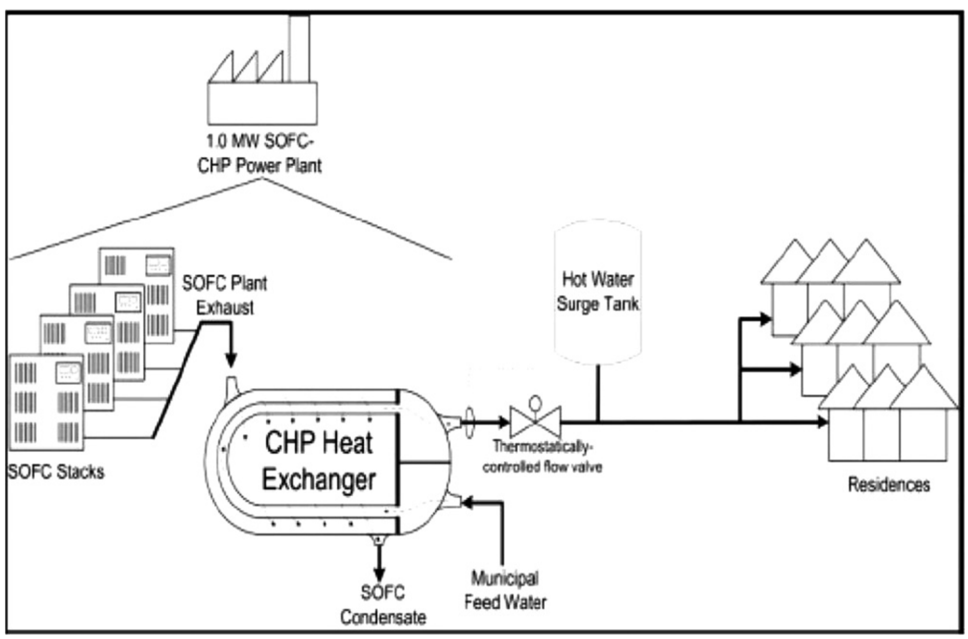

Fig. 7. SOFC-CHP system for residential application [43].

provide electricity and hot water to a 500-home residential neighbourhood more sustainably and avoiding substantial environmental emissions when compared to conventional power delivery. The simulation results show that for the residential case analyzed, hundreds of tons of carbon, sulphur, and nitrogen oxide emissions are avoided by reducing demand from conventional power sources (Fig. 7).

3.4. Trigeneration with SOFC

Trigeneration is a booming technology nowadays for efficient and clean production of energy. Trigeneration, also known as combined heating, cooling and power (CCHP) is a way of making the best use of the chemical energy of the fuel to generate electricity with the heat from the exhaust being utilized by providing heating. At the same time cooling can be produced from absorption or desiccant cooling, therefore reduces the consumption of electricity in a conventional air conditioning unit. Wu and Wang [44] performed extensive review on CCHP and found that most CCHP use fossil fuel as primary source of energy. CCHP system uses Otto cycle, GT, ST for trigeneration. Among them, CCHP system driven by fuel cell has achieved higher energy conversion efficiency because of all the advantages of fuel cell. Burer et al. [45] performed a thermo economic optimization of CCHP system comprising of SOFC technology. In the same way many researchers performed various analysis of CCHP system based on SOFC technology [46–48]. And found that the efficiency of the system increases by at least 22% when a trigeneration system is used. The exhaust gas of the SOFC–GT is still relatively high and in order to utilize this waste heat, and to improve the energy conversion efficiency, a combined cooling, heating and power system was proposed by Ma et al. [51] by using ammonia water mixture. The main fuel of the system is methane. The system can achieve an overall efficiency of up to 80% under the given condition. A detailed analysis of the trigeneration system shows that increasing fuel flow rate can increase the overall efficiency but decrease SOFC efficiency and electrical efficiency. On the other hand by increasing compressor pressure ratio, SOFC efficiency, electrical efficiency and overall efficiency increases (Fig. 8).

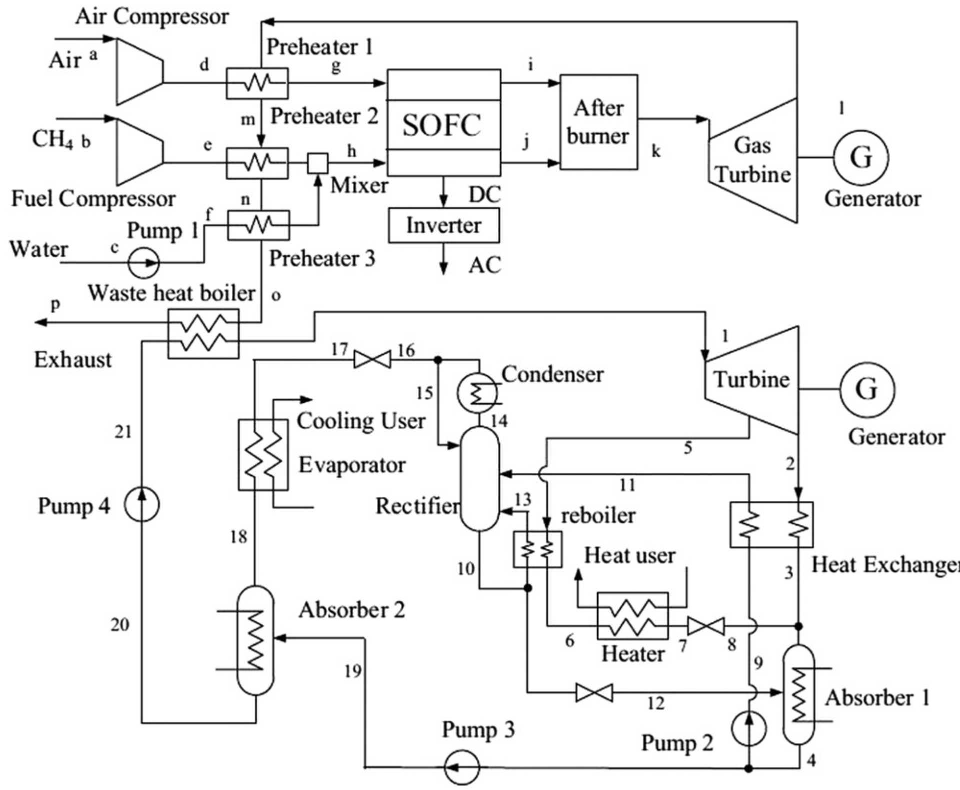

Fig. 8. Schematic diagram of CCHP system driven by SOFC [43].

3.5. SOFC–GT trigeneration system for marine application

According to the latest UN international Maritime report, shipping emitted 1.046 billion tons of CO_2 in the year 2050 and if it is not checked then it will increase up to 250% by 2050 which contribute to the global warming effect. Ship pollutes when docked and left idling. The most common power source for ship is large diesel engine but it produces noise and vibration as well as emissions such as CO_2, NO_x, and SO_x. In order to minimize these some instruments are installed which is cost intensive. One method of reducing CO_2 emissions on land is combined cooling heating and power (CCHP) or trigeneration, with typical combined thermal efficiencies of over 80%. In order to reduce fuel consumption and emissions some of the diesel engines are replaced by SOFC. But due to the long start up and stopping fuel cell are only used for auxiliary power unit (APU). A number of papers have been written considering SOFC trigeneration system for residential, office, hospital, airport etc. But no known paper has been written concerning the application of a solid oxide fuel cell–gas turbine-trigeneration system for marine applications. Chung Tse et al. [52] examined solid oxide fuel cell/gas turbine trigeneration system for marine applications. He investigates the feasibility of combining a SOFC–GT system and an absorption heat pump (AHP) in a trigeneration system to drive the heating ventilation and air conditioning (HVAC) and electrical base-load systems. Four configurations were proposed regarding SOFC trigeneration system for ships.

- SOFC–GT+conventional HVAC.
- SOFC–GT+absorption chiller +HVAC.
- SOFC–GT+desiccant wheel+HVAC.
- SOFC–GT+absorption chiller+desiccant wheel+HVAC.

A thermodynamic model was used to analyze the systems, with various configuration and cooling loads. Result showed that for the optimum configuration using a double effect absorption chiller, the net electric power increases by 47% relative to the electrical power available for a conventional SOFC GT–HVAC system. Thus overall efficiency is 12.1% for the conventional system, 34.9% for the system with single effect absorption chiller, 43.2% for the system with double effect absorption chiller. This shows that the overall efficiency of a trigeneration system is far higher when waste heat recovery happens (Fig. 9).

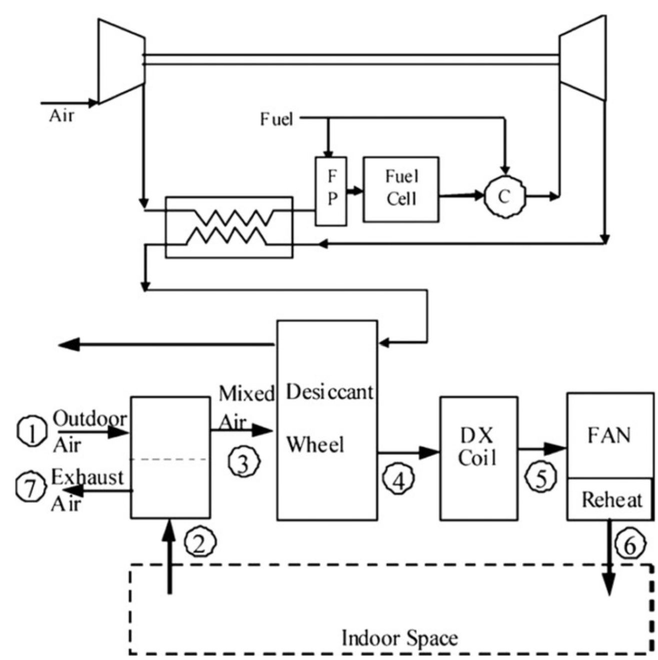

Fig. 9. Schematic diagram for the SOFC–GT–desiccant wheel–HVAC system [52].

3.6. SOFC for transportation

The compatibility of SOFC with hydrocarbon fuels makes SOFC a strong contender for transportation application [53,54]. Basically, a typical SOFC vehicle would be a hybrid fuel cell vehicle equipped with a small buffer battery and a relatively small on board SOFC power source which is more or less continuously converting conventional gasoline or diesel fuel into DC power. The temperature of the fuel cell will be adjusted to the actual power demand (Fig. 10).

Solid PEMFC need clean hydrogen. Hydrogen fuel is expensive and not easy to handle safely. Bulky, complex and costly converter is required to convert chemicals into hydrogen fuel. Moreover in hot climatic condition it is very difficult to maintain membrane humidification of PEMFC. Similarly in severe winter condition there is a problem of freezing of water. To remove the entire problem with PEMFC, SOFC is a good solution. Any fuel can be used with SOFC. There is a facility of internal reforming of fuel in SOFC. No noble metal catalyst is required in the process. The hot waste gasses are removed through exhaust pipe. There is no climatic restriction and driving range limitation. Also the high operating temperature of SOFC poses no serious problem. Also the large delay of starting time of SOFC can be bridged by energy from a buffer battery connected parallel to the fuel cell in the hybrid system. Furthermore, the output of SOFC can be varied over a decade by adjusting the operating temperature to the actual power requirement or the charge level of the buffer battery. Bossel [55] tabulated a brief comparison between PEMFC and SOFC powered vehicle (Table 2).

Bernay et al. [56] explained the prospect of different fuel cell technology for vehicle application. Proton exchanges membrane fuel cell (PEMFC), providing short starting and response times at the stack level seem to be the most suitable technology for drive application. In an auxiliary power unit application, the solid oxide fuel cell (SOFC), which allows easier operating with a traditional engine fuel because of simplified fuel processing and presents good performance, may find an application. Aguiar et al. [57] performed a feasibility study and techno-economic analysis for a SOFC/battery hybrid power system intended for vehicular traction applications and compared it with three promising vehicle technology i.e. only fuel cell based, battery based and IC Engine based vehicle. The hybrid consists of an intermediate temperature solid oxide fuel cell (IT-SOFC) operating at 500–800 °C and a sodium–nickel chloride (ZEBRA) battery operating at 300 °C. Such a hybrid system has the benefits of extended range and fuel flexibility (due to the IT-SOFC), high power output and rapid response time (due to the battery). The recent development of thin tubular solid oxide fuel cells (SOFCs), microturbines and Stirling engines has inspired design studies of the integration of a SOFC–heat engine (HE) system within a car. The total power system consists of a SOFC–HE power generation unit, a power storage (battery) system, a power management system and electric motors at the wheels. The sizes of the HE and the SOFC stack are to be matched by the start-up requirements.

Winkler and Lorenz [58] study the design of SOFC–Heat engine module for mobile application. The studies show that the optimal match of the SOFC and the HE will be a key issue for any engineering solution. Martinez et al. [59] assesses the feasibility of Solid Oxide Fuel Cell–Gas Turbine (SOFC–GT) hybrid power systems for use as the prime mover in freight locomotives. The space required to integrate SOFC–GT system is found to be similar to current diesel engines, without consideration of the electrical balance of plant. It is found that even in the diesel case, the SOFC–GT system provides significant savings in fuel and CO_2 emissions, making it an attractive option for the rail industry (Fig. 11).

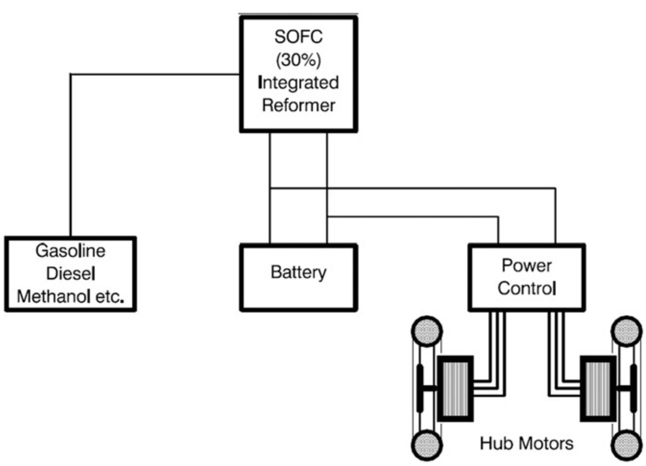

Fig. 10. SOFC-hybrid vehicle [55].

Table 2
Comparison of PEMFC and SOFC powered vehicle [55].

Features	PEFC powered vehicle	SOFC powered vehicle
Operating temperature	80 °C	750 °C
Stack power/weight	1 kw/Kg (approx.)	1 kw/Kg (approx.)
Overall efficiency	40%	50%
Operating range	800 KM (approx.)	1000 KM (approx.)
Cooling system	Required	Not required
System complexity	High	Low
Electrical system	Complex	Simpler
Fuel	Hydrogen	Natural gas/hydrogen gas
Start up time	Seconds	Minutes

3.7. SOFC for small scale residential application

High working temperature of solid oxide fuel cells (about 1000 °C) and high enthalpy of exhaust gases, environmental compatibility, simple maintenance, flexibility in fuel, low noise level as the result of absence of mechanical parts and ability of simultaneous heat and power production in kilowatt to megawatt level for different applications, have attracted the attention of researchers to use fuel cell energy recovery in different residential and industrial applications. Fuel cell can be used with combined heat and power system to provide the energy demands of building. Different researchers have worked in this field. They investigate the thermodynamic modelling of integrated SOFC-CHP/CCHP system for building. These models together with energy consumption models in building can estimate required fuel consumption based on energy production, analyze the compatibility of this cycle to different climatic condition, determine the size and characteristics of fuel cell and auxiliary equipments and finally suggest different control methods. Bos [60] investigated the system requirements and some design considerations for residential and small scale application of fuel cell-based systems. Bos optimized the fuel cell size to 2 kW. His analysis is primarily concerned with the commercialization and marketing strategies and did not explain the system component sizing, design, operating strategies and emission performance. Krist et al. [61] presented a discussion on design considerations and the potential effectiveness of SOFCs in residential applications. The authors in this paper demonstrate a fuel cell in the 1 kW size range based on thermal-to-electric ratios of residential loads. Operating and design strategies were discussed but they were not analyzed in detail. In addition, the authors demonstrate qualitative advantages of SOFCs over PEMFCs for residential cogeneration but did not perform any system studies or simulations to quantify these advantages. Sammes and Boersma [62] present a discussion of small-scale fuel cells for residential

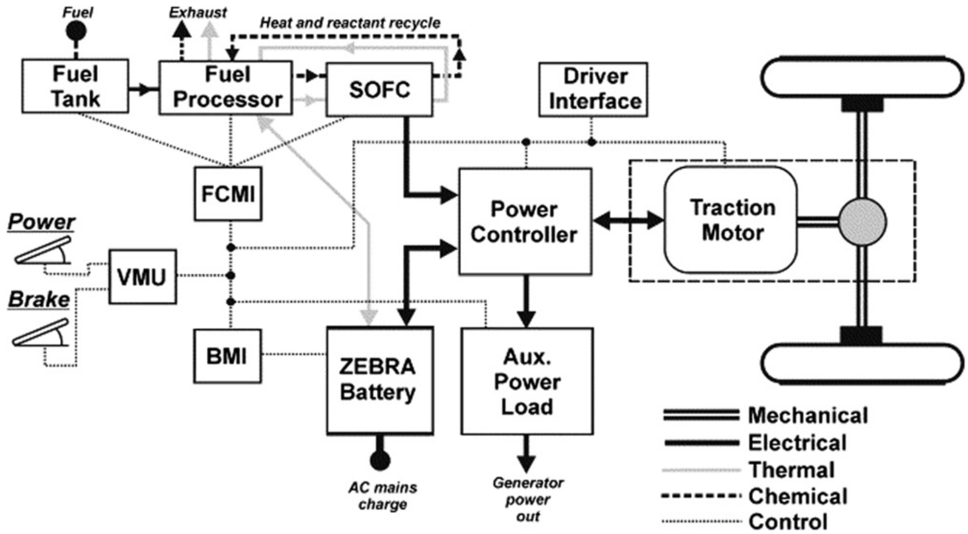

Fig. 11. SOFC-hybrid vehicle with traction motor [57].

applications but do not offer optimal designs or make performance comparisons between SOFCs and PEMFCs. In short their work mainly focuses on market and technical requirements of small scale fuel cells in residential applications and a survey of the various PEMFC and SOFC manufacturers but they do not present any design, system integration, or long-term performance of fuel cell systems that include energy storage. Farhad and Hamdullahpur [63] evaluate performance of different configurations of biogas-fuelled SOFC micro-CHP systems for residential applications. Baniasadi and Alemrajabi [64] in their work integrate a SOFC with the capacity of 215 kW with a recovery cycle for the sake of simultaneous of electric power, cooling load and domestic hot water demand of a hotel with 4600 m^2 area. They performed an energy and exergy analysis of the entire system. In addition they performed an economic study of simultaneous energy generation and recovery cycle in comparison with common residential power and energy systems. General results show that based on fuel lower heating value, the maximum efficiency of 83% for simultaneous energy generation and heat recovery cycle can be achieved on a climate condition of July in the afternoon, while all the electrical energy, cooling load and 40% of hot water demand could be provided by this cycle (Fig. 12).

3.8. Some miscellaneous applications

Ming Ni et al. [65] performed a literature review to investigate the performance of ammonia fed SOFC for power generation. It is found that NH_3 is a technically feasible fuel for direct use in SOFCs and the performance of NH_3-fed SOFC is comparable with that of the H_2 fed SOFC. Experimental study in literature also demonstrates that both oxygen ion-conducting electrolyte (SOFC-O) and proton-conducting electrolyte (SOFC-H) can be used in NH_3-fed SOFC, as the amount of NO_x generated in a SOFC-O is negligible. Fabricating thin film electrolyte and developing more reactive electrode materials are important to improve the performance of NH_3-fed SOFCs. Mathematical models are useful design tools for understanding the coupled transport and reaction phenomena and for optimizing the SOFC performance.

Koyama and Kraines [66] evaluate the tradeoffs between CO_2 emissions and cost in solid oxide fuel cell-based building energy systems. They built a simulation framework including solid oxide fuel cell (SOFC), a gas turbine, a double pipe heat exchanger, and a compressor for flexible evaluation of various distributed building energy systems based on the integration of component device simulation models. Through this model analysis they explore the optimal configuration of the SOFC/GT system and the optimal operation conditions of the SOFC system for the given electricity demand. Koyama et al. [67] in another paper built an integrated model framework for the evaluation of an SOFC/GT system as a centralized power source. DOME (distributed object-based modelling environment) was used to combine a simulation model for hybrid SOFC (solid oxide fuel cell) and gas turbine system with a power generation capacity and dispatch optimization model. The integrated models were used to evaluate the effectiveness of the system as a centralized power source for meeting the power demand in Japan. Evaluation results indicate that a hybrid system using micro-tube SOFC may reduce CO_2 emissions from power generation in Japan by about 50%. Park et al. [68] proposed an integrated power generation system combining solid oxide fuel cell (SOFC) and oxy-fuel combustion technology. The system consists of SOFC, gas turbine, oxy-combustion bottoming cycle, and CO_2 capture and compression process. It was found that the maximum efficiency of the system is over 69.2%.

Obara [69] investigates the operation of a SOFC–PEFC combined system, with time shift operation of reformed gas, into a microgrid with 30 houses in Sapporo, Japan. The SOFC is designed to correspond to base load operation, and the exhaust heat of the SOFC is used for production of reformed gas. This reformed gas is used for the production of electricity for the PEFC, corresponding to fluctuation load of the next day (Fig. 13). Accordingly, the reformed gas is used with a time shift operation. The relation between operation method, power generation efficiency, and amount of heat storage of the SOFC–PEFC combined system to the difference in power load pattern was investigated. The average power generation efficiency of the system can be maintained at nearly 48% on a representative day in February (winter season) and August (summer season). Fryda et al. [70] investigated an Integrated CHP with autothermal biomass gasification and SOFC–MGT. Auto thermal biomass gasification produces a gaseous fuel that, after gas cleaning and conditioning, can be used in solid oxide fuel cells (SOFC). This work comparatively investigates three small scale combined heat and power (CHP) configurations that integrate these technologies: (a) gasification at 4 bar and MGT, (b) gasification at 1.4 bar and SOFC and (c) gasification at 4 bar and SOFC–MGT. Interestingly, the MGT system proved more efficient than the atmospheric SOFC, both of which were surpassed by SOFC–MGT performance that reached an exergetic

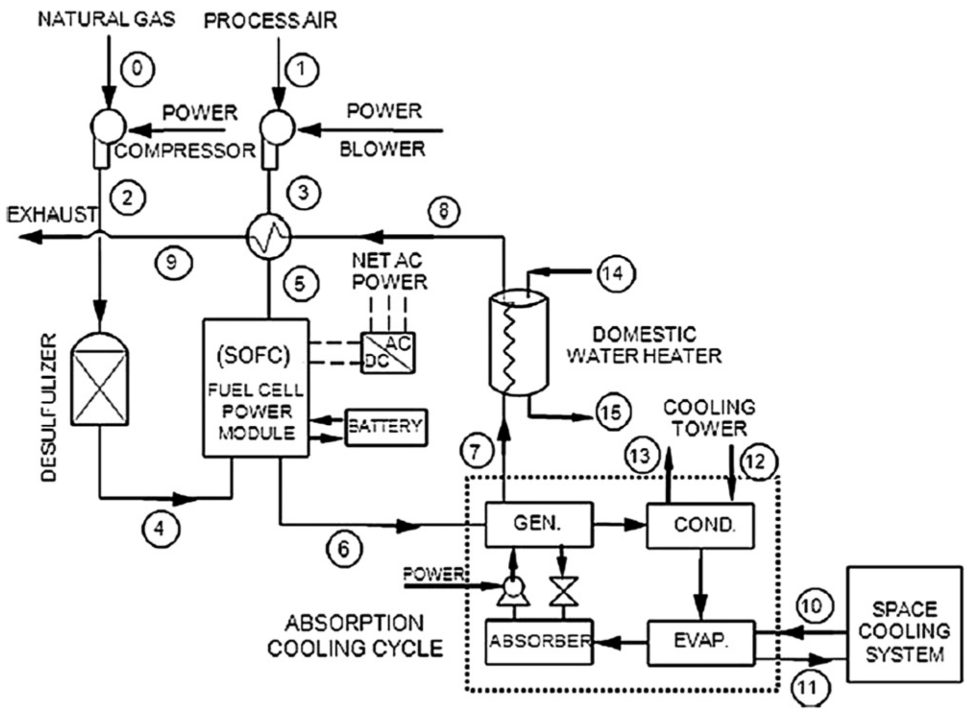

Fig. 12. SOFC trigeneration system for Hotel [64].

electrical efficiency of 35.6% using an SOFC of 100 m^2 active surface area and nominal biomass throughput of 200 kg/h. Application of Solid Oxide Fuel Cells (SOFC) in gasification-based power plants would represent a turning point in the power generation sector, allowing to considerably increase the electric efficiency of coal-fired power stations while reducing CO_2 and other pollutant emissions. A lot of work was performed in this sector by different researchers. Romano et al. [71] performs thermodynamic assessment of a SOFC-based IGFC plant with methanation reactor, hydrogen post-firing and CO_2 capture by physical absorption. The configuration proposed allows obtaining a very high net efficiency (51.6%). Wongchanapai et al. [72] developed a detailed anode-supported planar SOFC model under co-flow operation and a thermodynamic equilibrium for biomass gasification model and verify the model by reliable experimental and simulation data. The result shows that the increase in SOFC inlet temperature shows negative impact on system and gasifier performances while SOFC efficiencies are slightly increased. The number of cells required for SOFC is reduced with the increase of SOFC inlet temperature.

The Solid Oxide Cells (SOCs) are able to operate in two modes: (a) the Solid Oxide Fuel Cells (SOFCs) that produce electricity and heat and (b) the Solid Oxide Electrolyser Cells (SOEC) that consume electricity and heat to electrolyse water and produce hydrogen and oxygen. Panopoulos et al. [73] investigate a carbon free SOEC/SOFC combined system for the production of hydrogen, electricity and heat (tri-generation) from natural gas fuel. Hydrogen can be locally used as automobile fuel whereas the oxygen produced in the SOEC is used to combust the depleted fuel from the SOFC, which is producing electricity and heat from natural gas. Georgis et al. [74] study the design and operation of energy integrated solid oxide fuel cell (SOFC) systems for in situ hydrogen production and power generation. Two configurations are considered: one where the hot effluent stream from the fuel cell is used directly to provide heat to the endothermic reforming reaction, and another where the hot effluent streams are mixed and combusted in a catalytic burner before the energy integration.

Kim et al. [75] developed a compact SOFC power generation system by integrating a 1 kW SOFC stack and balance-of-plant. The system was designed for dual-fuel operation using both natural gas (NG) and liquefied petroleum gas (LPG). An adiabatic pre-reformer was employed in a fuel processing system to convert C_{2+} hydrocarbons in the fuel into CH_4-rich gas which was further processed in a main reformer to produce H_2-rich gas for the SOFC stack. The SOFC system was operated for 350 h under thermally self-sustaining condition, and on-load fuel switching from NG to LPG was carried out during the operation. It was found that the system performance was not significantly affected by NG/LPG composition ratios and the performance was stable during continuous operation in NG or LPG.

3.9. Recent researches in SOFC technology

- Researchers at the US Department of Energy's Pacific Northwest National Laboratory say that their new, small-scale solid oxide fuel cell system can achieve up to 57% efficiency—significantly higher than the 30–50% efficiencies previously reported for similarly sized SOFC systems [76].
- In Japan, Mitsubishi Heavy Industries (MHI) is developing the key technologies for a triple combined-cycle power generation system that integrates solid oxide fuel cells and a gas turbine combined-cycle (GTCC) power generation system. This combined system is expected to offer the highest efficiency of commercial power generation using SOFCs [77].
- In Japan, a consortium comprising Kyocera Corporation, Osaka Gas, Aisin Seiki Co Ltd, Chofu Seisakusho Co Ltd, and Toyota Motor Corporation have completed the co-development of a residential-use solid oxide fuel cell cogeneration system, which is now ready for commercialization [78].
- The US Department of Energy has announced further research funding of $500,000 for each of seven projects that will help develop low-cost solid oxide fuel cell technology for environmentally responsible central power generation from the nation's abundant coal resources [79].
- UK-based solid oxide fuel cell developer Ceres Power has reported 'significant progress' in improving the power degradation performance of its core technology and the reliability of

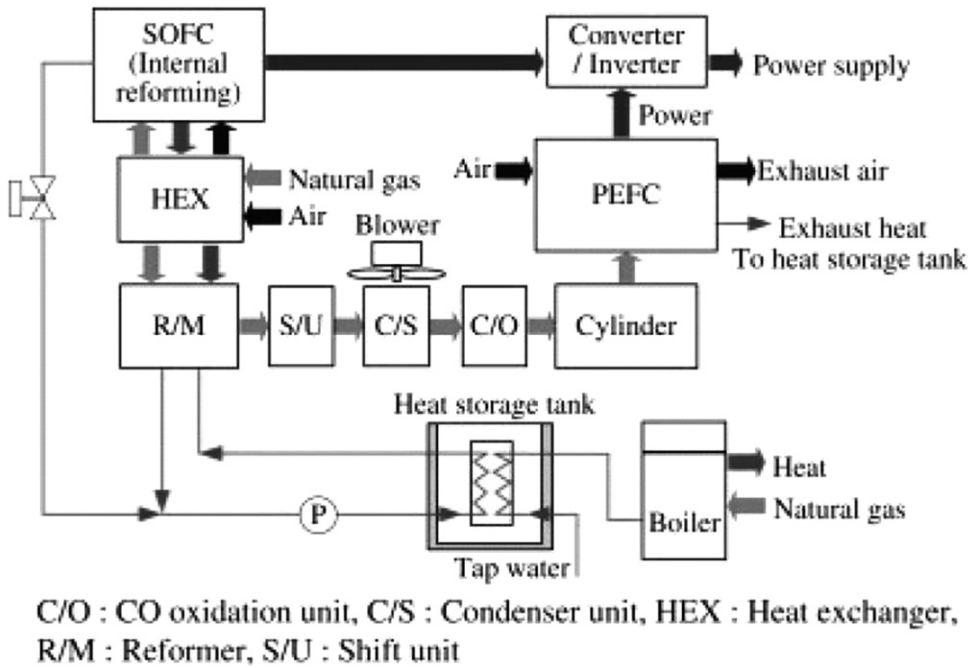

Fig. 13. SOFC–PEFC combined power system [69].

Table 3
Application of solid oxide fuel cell technology.

S. No.	Application	Power	Efficiency	Remarks
1.	SOFC–GT combined cycle	Several MW	Greater than 60%	Natural gas is used as fuel. SOFC can be integrated with GT directly or indirectly. Efficiency depends on configuration of system.
2.	SOFC-ST combined cycle	Several MW	Up to 67%	Natural gas is used as fuel. System efficiency depends on pre-reforming used. Efficiency of system with ARS pre-reforming is higher than CPO.
3.	Cogeneration with SOFC	200–300 kW for small scale application and several MW for industrial application	Greater than 80%	Natural gas/methane/pure hydrogen can be used as fuel.
4.	Trigeneration with SOFC	200–300 KW for small scale application and several MW for industrial application	System efficiency increases by at least 22%	Natural gas can be used as fuel.
5.	Transportation	2 kW per litre	Approx. 50%	Pure hydrogen or any hydrocarbon can be used as fuel. Recent developments suggests that SOFCs could play an important role in transportation.
6.	Residential	1–2 kW to 300 kW depending upon application	Up to 83%	Any fuel such as natural gas or pure hydrogen or biogas can be used as fuel.

its combined heat and power (CHP) product. The recent results mean that Ceres is on track to achieve the mass-market product specification required for launch in 2016 [80].

4. Conclusion

- High temperature SOFC provides a highly efficient, pollution free power generation. Electrical efficiency of over 70% are possible in SOFC based CHP/CCHP or combined cycle power plant.
- SOFC is an energy conversion device that uses oxide ion conducting ceramic material as electrolyte. So electrolyte management issues are absent here.
- The high operating temperature of SOFC provides internal reforming of fuel and also it can handle a wide range of hydrocarbon as fuel.
- The basic components of a SOFC power plant consist of a fuel processor, desulphurizer, fuel cell power module, power conditioning equipment for DC–AC converter and process gas heat exchanger. Depending upon the operating temperature SOFC fuel cell produce varying grades of waste heat that can be recovered for heating, cooling, cogeneration or trigeneration application purpose.
- There are three main application of SOFC such as combined cycle power plant, cogeneration/trigeneration for hotel, residential building etc. and transportation application.

- A brief review of the application of SOFC technology is tabulated in Table 3.

References

[1] Samuelsen, Scott. Fuel Cell/Gas Turbine Hybrid Systems, Professor Director National Fuel Cell Research Center, University of California Irvine, CA 92697-3550gss@nfcrc.uci.edu 〈http://www.nfcrc.uci.edu〉.
[2] Laosiripojana N, Wiyaratn W, Kiatkittipong W, Soottitantawat A, Assabumrungrat S. Reviews on solid oxide fuel cell technology. Engineering Journal 2009;13(1): 1–19.
[3] Singhal SC. Advances in solid oxide fuel cell technology. Solid State Ionics 2000;135:305–13.
[4] Stambouli ABoudghene, Traversa E. Solid oxide fuel cells (SOFCs): a review of an environmentally clean and efficient source of energy. Renewable and Sustainable Energy Reviews 2002;6:433–55.
[5] Wachsman Eric D, Singhal Subhash C. Solid Oxide Fuel Cell Commercialization, Research, and Challenges, the Electrochemical Society Interface, Fall 2009.
[6] Traversa Enrico. Toward the Miniaturization of Solid Oxide Fuel Cells, the Electrochemical Society Interface, Fall 2009.
[7] The Bloom Box: A Solid Oxide Fuel Cell. In 2010, after a "60 min" segment on the Bloom Box fuel cell aired on CBS, City Light commissioned the Wenatchi Group, Inc. to undertake a brief review of its applicability in City Light's service area.
[8] Massardo AF, Lubelli F. Internal reforming solid oxide fuel cell–gas turbine combined cycles (IRSOFC–GT): part A—cell model and cycle thermodynamic analysis, transactions of the ASME. Journal of Engineering for Gas Turbines and Power 2000;122(1):27–35.
[9] Larminie James, Dicks Andrew. Fuel cell explained. 2nd ed. Wiley Inc.; 2003.
[10] Selman JR. In: Blomen LJM, Mugerwa MN, editors. Research, development, and demonstration of molten carbonate fuel cell systems in fuel cell systems. New York, NY: Plenum Press; 1993. p. 419.
[11] Ide H, Yoshida T, Ueda H, Horiuchi N. Natural gas reformed fuel cell power generation systems—a comparison of three system efficiencies. In: Proceedings of the 24th intersociety energy conversion engineering conference, vol. 3. Washington, DC; 1989. p. 1517–1522.
[12] Costamagna P, Magistri L, Massardo AF. Design and part-load performance of a hybrid system based on a solid oxide fuel cell reactor and amicro gas turbine. Journal of Power Sources 2001;96(2):352–68.
[13] Chan SH, Ho HK, Tian Y. Modelling of simple hybrid solid oxide fuel cell and gas turbine power plant. Journal of Power Sources 2002;109(1):111–20.
[14] Chan SH, Ho HK, Tian Y. Multi-level modeling of SOFC–gas turbine hybrid system. International Journal of Hydrogen Energy 2003;28(8):889–900.
[15] Calise F, Palombo A, Vanoli L. Design and partial load exergy analysis of hybrid SOFC–GT power plant. Journal of Power Sources 2006;158(1):225–44.
[16] Yang WJ, Park SK, Kim TS, Kim JH, Sohn JL, Ro ST. Design performance analysis of pressurized solid oxide fuel cell/gas turbine hybrid systems considering temperature constraints. Journal of Power Sources 2006;160(1):462–73.
[17] Araki T, Ohba T, Takezawa Sh, Onda K, Sakaki Y. Cycle analysis of planar SOFC power generation with serial connection of low and high temperature SOFCs. Journal of Power Sources 2006;158(1):52–9.
[18] Park SK, Oh KS, Kim TS. Analysis of the design of a pressurized SOFC hybrid system using a fixed gas turbine design. Journal of Power Sources 2007;170(1):130–9.
[19] Granovskii M, Dincer I, Rosen MA. Performance comparison of two combined SOFC–gas turbine systems. Journal of Power Sources 2007;165(1):307–14.
[20] Cocco D, Tola V. Comparative performance analysis of internal and external reforming of methanol in SOFC–MGT hybrid power plants. Journal of Engineering for Gas Turbines and Power 2007;129(2):478–87.
[21] Haseli Y, Dincer I, Naterer GF. Thermodynamic analysis of a combined gas turbine power system with a solid oxide fuel cell through exergy. Thermochimica Acta 2008;480:1–9.
[22] Harvey SP, Richter HJ. A detailed study of a gas turbine cycle with an integrated internal reforming solid oxide fuel cell. In: Proceedings of 29th intersociety energy conversion engineering conference, vol. 2. Monterey, CA; 1994. p. 961–73.
[23] Chan SH, Ho HK, Tian Y. Modeling of simple hybrid solid oxide fuel cell and gas turbine power plant. Journal of Power Sources 2002;109(1):111–20.
[24] Lobachyov K, Richter HJ. Combined cycle gas turbine power plant with coal gasification and solid oxide fuel cell, transactions of the ASME. Journal of Energy Resources Technology 1996;118(4):285–92.
[25] Campanari S, Macchi E. Thermodynamic analysis of advanced power cycles based upon solid oxide fuel cells, gas turbines and rankine bottoming cycles. In: Inui Y, Yanagisawa S, Ishida T, Proceedings of the international gas turbine & aeroengine congress & exhibition, Stockholm, 1998. Proposal of high performance SOFC combined power generation system with carbon dioxide recovery, Energy Conversion and Management 2003;44(4):597–609.
[26] Uechi H, Kimijima Sh, Kasagi N. Cycle analysis of gas turbine–fuel cell cycle hybrid micro generation system. Journal of Engineering for Gas Turbines and Power 2004;126(4):755–62.
[27] Calise F, Denticed'Accadia M, Palombo A, Vanoli L. Simulation and exergy analysis of a hybrid solid oxide fuel cell (SOFC)–gas turbine system. Energy 2006;31(15):3278–99.
[28] Araki T, Taniuchi T, Sunakawa D, Nagahama M, Onda K, Kato T. Cycle analysis of low and high H_2 utilization SOFC/gas turbine combined cycle for CO_2 recovery. Journal of Power Sources 2007;171(2):464–70.
[29] Rao AD, Samuelsen GS. A thermodynamic analysis of tubular solid oxide fuel cell based hybrid systems, transactions of the ASME. Journal of Engineering for Gas Turbines and Power 2003;125(1):59–66.
[30] George RA. SOFC combined cycle systems for distributed generation. In: Proceedings of the American Power Conference, Chicago, IL, vol. 59-1 (1997) 548–550.
[31] Inui Y, Yanagisawa S, Ishida T. Proposal of high performance SOFC combined power generation system with carbon dioxide recovery. Energy Conversion and Management 2003;44(4):597–609.
[32] Rokni Masoud. Thermodynamic analysis of an integrated solid oxide fuel cell cycle with a Rankine cycle. Energy Conversion and Management 2010;51: 2724–32.
[33] Fontell E, Kivisaari T, Christiansen N, Hansen J, Pålsson J-B. Conceptional study of a 250 kW planar SOFC system for CHP application. Journal of Power Sources 2004;131:49–56.
[34] Rokni M. Introduction of a fuel cell into combined cycle: a competitive choice or future cogeneration. ASME Cogen—Turbo IGTI 2003;8:255–61.
[35] Riensche E, Achenbach E, Froning D, Haines MR, Heidug WK, Lokurlu A, et al. Clean combined-cycle SOFC power plant–cell modeling and process analysis. Journal of Power Sources 2000;86:404–10.
[36] Dunbar WR, Lior N, Gaggioli RA. Combining fuel cells with fuel-fired power plants for improved exergy efficiency. Energy 1991;16(10):1259–74.
[37] Chan SH, Low CF, Ding OL. Energy and exergy analysis of simple solid-oxide fuel-cell power systems. Journal of Power Sources 2002;103:188–200.
[38] Fontell E, Kivisaari T, Christiansen N, Hansen JB, Palsson J. Conceptual study of a 250 kW planar SOFC system for CHP application. Journal of Power Sources 2004;131:49–56.
[39] Omosun AO, Bauen A, Brandon NP, Adjiman CS, Hart D. Modelling system efficiencies and costs of two biomass-fuelled SOFC systems. Journal of Power Sources, Selected papers presented at the Eighth Grove Fuel Cell Symposium 2004;131:96–106.
[40] Bang-Møller C, Rokni M, Elmegaard B. Exergy analysis and optimization of a biomass gasification, solid oxide fuel cell and micro gas turbine hybrid system. Journal of Energy 2011:1–13.
[41] Zink F, Lu Y, Schaefer L. A solid oxide fuel cell system for buildings. Energy Conversion and Management 2007;48:809–18.
[42] Braun RJ, Klein SA, Reindl DT. Evaluation of system configurations for solid oxide fuel cell-based micro combined heat and power generators in residential applications, Journal of Power Sources, Special issue including selected papers from the 6th International Conference on Lead-Acid Batteries (LABAT 2005, Varna, Bulgaria) and the 11th Asian Battery Conference (11 ABC, Ho Chi Minh City, Vietnam) together with regular papers, vol. 158; 2006. p. 1290–305.
[43] Colson CM. Student Member, IEEE, and M.H. Nehrir, Fellow, IEEE, Evaluating the benefits of hybrid SOFC-CHP for energy sustainability and emission avoidance, IEEE Transactions on Energy Conversion, vol. 26, no. 1; March 2011.
[44] Wu DW, Wang RZ. Combined cooling, heating and power: A review, Progress in Energy and Combustion Science 2006;32:459–95.
[45] Burer M, Tanaka K, Favrat D, Yamada K. Multi-criteria optimization of a district cogeneration plant. Energy 2003;28:497–518.
[46] Liu Y, Leong KC. Journal of Power Sources 2006;159:501–8.
[47] Yu ZT, Han JT, Cao XQ, Chen W, Zhang B. Analysis of total energy system based on solid oxide fuel cell for combined cooling and power applications, International Journal of Hydrogen Energy 2010;35:2703–7.
[48] Al-Sulaiman FA, Dincer I, Hamdullahpur F. Energy analysis of trigeneration plant based on solid oxide fuel cell and ORC, International Journal of Hydrogen Energy 2010;35:5104–13.
[49] Massardo AF, McDonald CF, Korakianitis T. Microturbine/ fuel-cell coupling for high-efficiency electrical-power generation. Transactions of the ASME. Journal of Engineering for Gas Turbines and Power 2002;124(1):110–6.
[50] Tse L, Galinaud F, Martinez-Botas RF. Integration of solid oxide fuel cells into a gas turbine cycle, ASME turbo expo power for land. Sea and Air, 〈http://www.felicitas-fuel-cells. info/files/061101_ASME2007_Tse.pdf〉 2007. Palais Des Congres Montreal DRAFT.
[51] Ma Shaolin, Wang Jiangfeng, Yan Zhequan, Dai Yiping, Lu Bingheng. Thermodynamic analysis of a new combined cooling, heat and power system driven by solid oxide fuel cell based on ammonia–water mixture. Journal of Power Sources 2011;196:8463–71.
[52] Chung Tse Lawrence Kar, Wilkins Steven, McGlashan Niall, Urban Bernhard, Martinez-Botas Ricardo. Solid oxide fuel cell/gas turbine trigeneration system for marine applications. Journal of Power Sources 2011;196:3149–62.
[53] Kendall K, Kilbride I, Palin M, Copcutt R. Zirconia fuel cells for the car of tomorrow. European Fuel Cell News, vol. 3, No. 2; 1996.
[54] Chen Y, Evans JW. Cool-down time of solid oxide fuel cells intended for transportation application. Journal of Power Sources 1996;58:87–91.
[55] Bossel G. Solid oxide fuel cells for transportation. In: Proceedings of the 3rd european SOFC forum, Nantes/France, Order from: European Fuel Cell Forum, POB 99, CH-5452 Oberrohrdorf/ Switzland; 1998.
[56] Bernay C, Marchand M, Cassir M. Prospect of different fuel cell technology for vehicle application. Journal of Power Sources 2002;108:139–52.
[57] Aguiar P, Brett DJL, Brandon NP. Feasibility study and techno economic analysis of an SOFC/battery hybrid system for vehicle applications. Journal of Power Sources 2007;171:188–97.

[58] Winkler Wolfgang, Lorenz Hagen. Design studies of mobile applications with heat engine module. Journal of Power Sources 2002;106:338–43.

[59] Martinez Andrew S, Brouwer Jacob, Samuelsen GScott. Feasibility study for SOFC–GT hybrid locomotive power part II. System packaging and operating route simulation. Journal of Power Sources 2012;213:358–74.

[60] Bos PB. Commercializing fuel cells: managing risks. Journal of Power Sources 1996;61:21–31.

[61] Krist K, Gleason K,Wright J. SOFC-based residential cogeneration systems. In: Proceedings of sixth international symposium on solid oxide fuel cells (SOFC-VI), Honolulu, HI, PV99-19. Electrochemical Society; 1999. p. 107–115.

[62] Sammes NM, Boersma R. Small-scale fuel cells for residential applications. Journal of Power Sources 2000;86(1–2):98–110.

[63] Farhad S, Hamdullahpur F. Assessment of performance evaluation of different configurations of biogas-fuelled SOFC micro-CHP systems for residential applications. International Journal of Hydrogen Energy 2010.

[64] Baniasadi Ehsan, Alemrajabi Ali Akbar. Fuel cell energy generation and recovery cycle analysis for residential application. International Journal of Hydrogen Energy 2010;35:9460–7.

[65] Meng Ni Michael, Leung KH, Leung YC. Ammonia-fed solid oxide fuel cells for power generation—a review. International Journal of Energy Research 2009;33: 943–59.

[66] Koyama Michihisa, Kraines Steven. A flexible model integration approach for evaluating tradeoffs between CO_2 emissions and cost in solid oxide fuel cell-based building energy systems. International Journal of Energy Research 2005;29:1261–78.

[67] Koyama Michihisa, Kraines Steven, Tanaka Kanako, Wallace David, Yamada Koichi, Komiyama Hiroshi. Integrated model framework for the evaluation of an SOFC/GT system as a centralized power source. International Journal of Energy Research 2004;28:13–30.

[68] Park Sung Ku, Kim Tong Seop, Sohn L, Lee Young Duk. An integrated power generation system combining solid oxide fuel cell and oxy-fuel combustion for high performance and CO_2 capture. Applied Energy 2011;88:1187–96.

[69] Obara Shin'ya. Power generation efficiency of an SOFC–PEFC combined system with time shift utilization of SOFC exhaust heat. International Journal of Hydrogen Energy 2010;35(2):757–67.

[70] Fryda L, Panopoulos KD, Kakaras E. Integrated CHP with autothermal biomass gasification and SOFC–MGT. Energy Conversion and Management 2008;49: 281–90.

[71] Romano Matteo C, Spallina Vincenzo, Campanari Stefano. Integrating IT-SOFC and gasification combined cycle with methanation reactor and hydrogen firing for near zero-emission power generation from coal. Energy Procedia 2011;4:1168–75.

[72] Wongchanapai Suranat, Iwai Hiroshi, Saito Motohiro, Yoshida Hideo. Performance evaluation of an integrated small-scale SOFC-biomass gasification power generation system. Journal of Power Sources 2012;216:314–22.

[73] Panopoulos KD, Hofmann Ph, Spyrakis S, Kakaras E. Design and exergetic analysis of a novel carbon free tri-generation system for hydrogen, power and heat production from natural gas, based on combined solid oxide fuel and electrolyser cells. International Journal of Hydrogen Energy 2010; 35(6): 2446–2456.

[74] Georgis Dimitrios, Jogwar S, Almansoori S, Daoutidis Prodromos. Design and control of energy integrated SOFC systems for in situ hydrogen production and power generation. Computers & Chemical Engineering 2011;35: 1691–704.

[75] Kim Yongmin, Hong Seong-Ahn, Nam Suk Woo, Seo Seok-Ho, Yoo Young-Sung, Lee Sang-Houck. Development of 1 kW SOFC power package for dual-fuel operation. International Journal of Hydrogen Energy 2011;36: 10247–54.

[76] PNNL reports record efficiency for small SOFC for homes, http://dx.doi.org/10.1016/S1464-2859(12)70211-0.

[77] Mitsubishi to develop SOFC-turbine triple combined cycle system, http://dx.doi.org/10.1016/S1464-2859(12)70197-9.

[78] Japanese group unveils SOFC Ene-Farm residential cogen unit, http://dx.doi.org/10.1016/S1464-2859(12)70093-7.

[79] Ceres power reports significant progress with SOFC CHP tech, http://dx.doi.org/10.1016/S1464-2859(12)70164-5.

[80] DOE awards for seven SOFC projects that run cleanly on coal, http://dx.doi.org/10.1016/S1464-2859(12)70272-9.